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POTENTIAL RADIOLOGICAL IMPACT OF AIRBORNE RELEASES AND DIRECT GAMMA RADIATION TO INDIVIDUALS LIVING NEAR INACTIVE URANIUM MILL TAILINGS PILES

Office of Radiation Programs, Washington, D. C.

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POTENTIAL RADIOLOGICAL IMPACT OF AIRBORNE RELEASES AND DIRECT GAMMA RADIATION TO INDIVIDUALS LIVING NEAR INACTIVE URANIUM MILL TAILINGS PILES

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January 1976

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i.

FOREWORD

The Office of Radiation Programs carries out a National Program designed to evaluate the exposure of man to ionizing and nonionizing radiation and to promote development of controls necessary to protect the public health and safety and assure environmental quality.

As man's appreciation of the risks of exposure to radiation has developed, an awareness has developed that the tailings piles of inactive uranium mills may be causing a risk to the public from radiation of sufficient magnitude to warrant remedial action and development of necessary controls. As part of a cooperative program with the Energy Research and Development Administration to assess the risk and provide remedial action if needed, this report has been prepared to provide a basis for an initial assessment of the potential radiation doses from the tailings piles, and to point out the kinds of information needed to prepare a thorough evaluation of the local radiation risks from individual tailings piles.

Comments on this analysis would be appreciated. These should be sent to the Director, Environmental Analysis Division, of the Office of Radiation Programs.

W. D. Rowe, Ph.D.
Deputy Assistant Administrator
for Radiation Programs

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Potential Radiological Impact of Airborne Releases and Direct Gamma Radiation to Individuals Living Near Inactive Uranium Mill Tailings Piles

Abstract

As part of a program to determine which measures to use to control radioactivity from tailings piles at inactive uranium mills, the U.S. Environmental Protection Agency has prepared estimates of the potential for exposure to radioactivity presented by these piles. The gamma radiation field and the radon-222 release rate are estimated on the basis of the radium-226 concentration in each pile. Potential exposures to airborne particulate uranium, thorium-230 and radium-226 are estimated from field measurements. Dispersion of airborne material was calculated with adaptations of computer codes which are common models for annual-average and single plume dispersion.

The estimated potential annual dose from radioactive radon decay products to individuals in dwellings in the vicinity of an average inactive pile is approximately 8 rem to the tracheobronchial region of the lungs at about 50 meters from the pile, 0.3 rem at 1 kilometer, and 0.1 rem at about 3.2 kilometers. The corresponding doses to the pulmonary region of the lungs from airborne uranium thorium-230, and radium-226 are estimated to be about one-third as large, within 1 kilometer of the pile. Gamma exposure rates on the tailings are up to 1 mR/hr. Estimated exposure rates are in reasonable agreement with the limited data from field measurements.

Should an individual be exposed continuously to a dose equivalent of 8 rem/yr to the tracheobronchial region of the lung, it would require 100 years of exposure to double his risk of bronchial cancer. Also, this level of exposure is considered equivalent to 0.5 Working Level Months per year, which is approximately 1/10 of the radiation protection guidance for the protection of underground uranium miners issued by the Environmental Protection Agency. Average individuals exposed over a lifetime to a dose equivalent of 0.1 rem/yr and 0.1 rem/yr would increase their risk of bronchial cancer by about 1 percent and 1 percent respectively.

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Although there are uncertainties in these estimates, the indicated conclusions are that the radon releases, which are difficult to control, are the hazard of greatest significance, that the radioactive particulate matter releases may sometimes be significant also, and that thorough measurements are needed for assessment of individual piles.

The potential national and worldwide radiological impact of radon-222 was not evaluated.

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1.0 Summary

This study is part of an evaluation of abandoned uranium mill tailings to determine the need for remedial measures to reduce their radiological health effects. The public health significance of the mill tailings was estimated on the basis of average conditions for 20 inactive mill sites. While this assessment may not typify actual conditions at all uranium mill tailings sites, several important observations were made. First, both theoretical estimates and experimental evidence indicate that individuals in the general population may be receiving high radiation doses to the lung as a result of the release of radon and its short-lived daughter products. Respirable airborne tailings particles bearing radionuclides provide another significant mode of potential radiation exposure at small downwind distances, as does the gamma radiation emitted from the tailings piles. Secondly, in order to accurately assess the potential public health significance of uranium tailings sites for purposes of determining remedial measures, a more comprehensive assessment of the problem using actual data applicable to existing sites rather than assumptions applicable to a model site is required.

This report has two main objectives: (1) to assess realistically the potential radiological implications of airborne releases and direct gamma radiation from inactive uranium mill tailings sites, and (2) to discuss the uncertainties inherent in each aspect of the present assessment methodology.

The radiological assessment of the radon-222 emissions indicates that the estimated annual average dose from radon-222 decay products to individuals in dwellings in the vicinity of an average uranium tailings site is approximately 8 rem to the lungs at about 50 meters from the pile, 0.3 rem at 1 kilometer, and 0.1 rem at approximately 3.2 kilometers. The radiological effects of windblown particulates containing thorium-230 and radium-226 were also evaluated and were determined to be less of a problem. While there is the possibility of doses to nearby individuals from these radionuclides fully as large as those from decay products of radon-222, the annual dose to the lungs of an individual within 1 kilometer of the pile from uranium, thorium, and radium is estimated conservatively to be about one-third as large. For a typical uncovered tailings pile, the external gamma dose rate is estimated to be 10 rem/yr at 3 feet from the surface of the pile, decreasing to less than 1 mrem/yr at 1.0 kilometer.

It is estimated that the average individual exposed continuously over a lifetime to a dose equivalent of 8 rem/yr to the bronchial epithelium region of the lung will incur about a 70 percent increase in the risk of bronchial cancer. Average individuals similarly exposed to a dose equivalent of 0.1 rem/yr and

0.1 rem/yr would increase their risk of bronchial cancer by about 3 percent and 1 percent respectively. The relative risk from particulate material blown from the pile is not as critical, because the radiation dose from inhaled radioactive particles is lower and, in addition, is delivered to the pulmonary region of the lung. Irradiation of the pulmonary lung is believed to be less likely to produce a health effect compared to an identical dose equivalent delivered to the bronchial epithelium. The relative increase in risk caused by gamma radiation from the average tailings pile is also estimated to be less significant than the increase in risks caused by radon-222 from the pile.

1.0 Introduction

1.1 Background

In March 1974, the U.S. Environmental Protection Agency and the U.S. Atomic Energy Commission testified at hearings before the Joint Committee on Atomic Energy (JCAE) to present their respective views on pending bills S-2946 and HR-11378. These were identical bills which provided for a cooperative program between the AEC and the State of Utah for the stabilization and containment of a uranium tailings pile at the site of the now inactive Vitro Mill near Salt Lake City, Utah. Both Federal agencies acknowledged that there are other uranium tailings sites besides the Vitro Mill tailings pile that may present public health problems, and that legislation that deals with all inactive mill sites and not just a single site would be more effective in controlling these potential problems. Consequently, both the EPA and the AEC recommended and subsequently proceeded to implement a study to determine the current condition of all inactive uranium mill sites in the various states. This study is a cooperative two-phase undertaking involving the states concerned and appropriate Federal agencies.

Phase I involved a visit to each site to determine the physical conditions of the site, need for remedial action, ownership, proximity to populated areas, prospects that the number of people living around the site would increase, approximate areas of tailings, etc. A preliminary report, which will serve as a basis for determining if additional assessment is necessary, was prepared for each site. These reports were provided to the JCAE (October 1974) before proceeding with Phase II.

Phase II of the study, which started in July 1975, includes a detailed radiological and engineering assessment of the piles, an examination of alternative remedial measures and the preparation of cost estimates, detailed plans and specifications for various remedial actions.

This part of the study also includes extensive physical measurements to determine the degree of potential radiation exposure of the public. Additional research and development may be needed on stabilization techniques to prevent wind and water erosion of the tailings piles and to prevent radon emission from them. An assessment will be made of the total environmental impact of proposed remedial actions.

The EPA has recently attempted to quantify the potential public health problems associated with uranium mill tailings at both active and discontinued milling operations and place them in perspective relative to other segments of the uranium fuel cycle. The results of these analyses are contained in reference (1).

These analyses were done on the basis of a model tailings pile which was assumed to be representative of all tailings sites. Numerous assumptions were made where information was lacking or where large uncertainties existed with the available information. This generic assessment indicated that uranium mill tailings piles present possible radiological health problems and that a more rigorous analysis of them is required.

Uranium mill tailings piles contain most of the decay products of the radioactive decay of uranium and a little residual uranium. The principal radionuclides of concern, in order of their appearance in the decay chain, are thorium-230, radium-226, radon-222, polonium-218, lead-214, bismuth-214, polonium-214, and polonium-210.

Uranium mill tailings piles release airborne radioactivity as radon gas and also as airborne particulates when wind blowing over the pile lifts material into the air. Radioactivity may be leached from the pile into surface and ground water by precipitation and by surface runoff waters. Also, sufficient radioactivity is in the tailings to create a field of gamma radiation in the vicinity of the tailings. Because of the presence of thorium-230 in the tailings, which by its decay maintains the radium inventory, the radioactivity in the pile can remain almost constant for thousands of years. The scope of these problems and the remedial actions required for their control vary with each site and, therefore, must be determined for each inactive tailings pile.

2.0 Present State of Knowledge

The Environmental Protection Agency and its predecessor radiological health program in the U.S. Public Health Service have been active for years in programs to determine the nature and magnitude of the public health problems associated with uranium tailings. More widespread appreciation of the magnitude of the problems involved has brought more support for these programs.

Under a joint agreement between the AEC and PHS, a project was begun in June 1967, in cooperation with the Colorado Department of Public Health and the Utah State Division of Health to evaluate the public health aspects of atmospheric concentrations of radon-222 in the vicinity of uranium tailings piles. The objectives of this project were to (1) develop techniques for taking integrated air samples for radon near uranium tailings piles, (2) evaluate atmospheric concentrations of radon in areas near tailings piles as an index of radiation exposure to the population, (3) determine the effect of stabilization and covering on the emission of radon gas from tailings piles, and (4) develop joint recommendations (or guidelines), if necessary, to control exposures based upon measured radon concentrations. The results of the study are reported in a 1969 DHEW publication titled "Evaluation of Radon-222 Near Uranium Tailings Piles" (3).

Study areas were chosen to reflect conditions at both operating and inactive uranium mills. Locations were chosen at Grand Junction, Colorado (then an operating mill with uncovered tailings), Durango, Colorado (inactive mill, uncovered tailings), and Monticello, Utah (inactive mill, covered tailings). The Vitro Mill tailings pile near Salt Lake City, Utah, was added to the study in October 1967. The Vitro Mill tailings were uncovered, and the mill ceased operation in July 1968, while the study was being conducted. At each of these study areas, a number of sampling sites were selected that were representative of onsite, near-pile, and general community conditions. Locations were chosen taking into consideration the prevailing wind patterns, population densities, and geographical factors.

Table 2.2-1 summarizes the measured radon concentrations at onsite and offsite sampling stations at the four study areas. For perspective, these values may be compared with the following regulations and guides.

Federal regulations 10 CFR Part 20 (3) presently permit AEC licensed operations to release average concentrations of radon-222 to the air in unrestricted areas of 3×10^{-9} μCi/ml (3 pCi/l) above natural background. (Such releases may be subject to reduction if it appears that a suitable sample of an exposed population may have an intake of the decay product radionuclides greater than they would have if exposed to average concentrations of one-third of the 3×10^{-9} μCi/ml, i.e., 1 pCi/l.)

Recommendations of the International Commission on Radiological Protection (ICRP) state that the annual radiation dose limits for individual members of the general public should be one-tenth of the corresponding annual occupational dose for com-

Table 2.2-1. Summary of Onpile and Offpile Stations at the Four Study Areas

(From "Evaluation of Radon-222 Near Uranium Tailings Piles" (2))

Location	Number of stations	Total number of samples	Concentration of radon-222 pCi/m³ average[a]	Range
Grand Junction, Colo.				
Onpile	5	85	7.8	1.1 - 28.0
Near-pile	4	68	1.9	.50 - 4.5
Other	16	262	0.83[b]	.13 - 4.4
Durango, Colo.				
Onpile	2	30	10.0	.48 - 34.0
Station 54[c]	1	10	1.4	.44 - 2.3
Other	4	72	0.51[b]	.09 - 1.4
Monticello, Utah				
Onpile	4	22	3.9	.12 - 18
Offpile	8	151	0.34[b]	.03 - 1.1
Salt Lake City, Utah				
Onpile	1	16	10	1.6 - 28
Station 82[d]	1	11	4.2	2.1 - 6.6
Offpile	10	150	0.38[b]	.06 - 1.4

(a) average of about 17 measurements at each location over a period of 11 months

(b) assumed to be the local background concentration

(c) about 0.4 mi southeast of site

(d) about 0.4 mi west of site

tinuous exposure as listed in the Committee II report (4). Application of these recommendations to the 168-hour concentration (10 pCi/l) for occupational exposure to radon-222 (with daughter products present at equilibrium concentrations) leads to a value of 1 pCi/l for continuous exposure to individuals in the general population. This concentration is in addition to the natural background radon concentration which is on the order of 0.1 pCi/l.

More recently, EPA has conducted environmental surveys (5) around the uranium tailings pile at the site of the now inactive Vitro Mill near Salt Lake City, Utah. The surveys included measurement of external gamma radiation and airborne radioactivity. The results of the surveys indicated that the external radiation levels on the tailings area exceeded recommended dose equivalent limits for individuals in the general population (500 mrem/yr), that ambient levels of radon over the pile and in some of the structures built immediately adjacent to the tailings pile were above the currently recommended concentrations for individuals in the general population (1 pCi/l), and that the working level (WL) exposures in the adjacent buildings exceed 0.01 WL. The relation between radon concentrations in pCi/l and working level (WL) is discussed in section 1.1.

Because the mill tailings piles have not been the subject of as much interest as some other sources of radiation, there has been little development of methods specifically designed for estimating exposures to radiation originating with the pile. Schiager (6) presents methods that require minimal data inputs for estimating potential radiation exposures from abandoned uranium tailings piles based upon the average radium concentration in the tailings. The reductions in exposure rates that can be achieved by covering the tailings with earth or concrete are also discussed. Based upon a case study of data on one tailings pile (Vitro pile), Schiager concludes that contributions to the average annual outdoor radon daughter concentrations exceeding 0.001 WL are very unlikely on or near any tailings pile. However, estimates of indoor radon daughter concentrations under the same conditions, which would lead to a more accurate assessment of potential radiation exposures for most sites, are not presented.

1.0 Radiological Assessment of Emissions from Uranium Mill Tailings Piles

Mill tailings piles present a potential for exposure to radiation by several pathways. The most important pathway is believed to be that of the radon-222. Radium-226 in the pile decays by alpha particle emission and becomes radon-222, a radioactive noble gas. The radon-222 gas that is released into the spaces between the grains

of tailings material diffuses toward the overlying tailings surface; some reaches the surface and some undergoes radioactive decay enroute. The radon-222 that reaches the surface escapes into the air above, where it is mixed into the passing airstream by normal local air turbulences. The wind carries the radon-222 with it and continually decreases the concentration by further mixing and dilution. Persons downwind of the tailings pile will be exposed to some concentration of radon-222 and its particulate radioactive decay products in the air they breathe. The air that enters a building downwind remains inside it for some period of time, depending on the ventilation rate, i.e., on the rate at which air enters and leaves the building. The radon-222 in the air undergoes its normal rate of radioactive decay, forming a series of decay products which may be inhaled by persons in the building. Some of the radioactive daughters of the radon-222 are retained in the tracheobronchial region of the lungs, irradiating the fluids and tissues, and thus increasing the risk of cancer formation there. In contrast, persons outdoors who are exposed to the same radon-222 concentration from a nearby tailings pile may receive an exposure to the lungs from the radon decay products which is appreciably smaller (e.g., a factor of 10) than that received indoors, due to the lack of a delay time which permits daughter product ingrowth.

Another pathway for exposure to radiation is that in which the wind lifts particles containing radionuclides from the surface of the tailings pile and carries them downwind, with simultaneous mixing, dilution, and deposition, until they reach persons inside or outside of buildings. Inhalation of the particles leads to exposure in several ways, but it is believed that the principal exposure is to the pulmonary region (the exchange space, non-ciliated) of the lungs in this case. It is likely that indoor exposures by this pathway are smaller than those outdoors because filtration and sedimentation processes reduce the particle concentrations.

The third principal pathway for exposure to radiation from the tailings piles is that in which the radionuclides in the pile emit gamma radiation which may penetrate the overlying material and air to interact with the body tissues of persons on or near the tailings piles.

The decay chain containing radon-222 and daughters is shown in figure 3.0-1.

3.1 Radioactivity Emitted from Tailings Piles

3.1.1 Radon

Most of the uranium ores being milled in this country are sandstones consisting of silica grains poorly cemented together

Productions of Radon-222

^{238}U —(4.2 MeV α, 4.51 × 10^9 yr)→ ^{234}Th —(0.19 MeV β, 24.1 days)→

^{234}Pa —(2.3 MeV β, 1.17 min)→ ^{234}U —(4.7 MeV α, 2.47 × 10^5 yr)→

^{230}Th —(4.6 MeV α, 8.0 × 10^4 yr)→ ^{226}Ra —(4.8 MeV α, 1,600 yr)→ ^{222}Rn

Short Half-Life Radioactive Decay Products of Radon-222

^{222}Rn —(5.5 MeV α, 3.82 days)→ ^{218}Po (RaA) —(6.0 MeV α, 3.05 min)→

^{214}Pb (RaB) —(0.7 MeV β, 26.8 m)→ ^{214}Bi (RaC) —(3.3 MeV β, 19.7 min)→

^{214}Po (RaC') —(7.7 MeV α, 164 μ sec)→ ^{210}Pb (RaD)

Long Half-Life Radioactive Decay Products of Radon-222

^{210}Pb (RaD) —(0.02 MeV β, 21 yr)→ ^{210}Bi (RaE) —(1.2 MeV β, 5.01 days)→

^{210}Po (RaF) —(5.3 MeV α, 138 days)→ ^{206}Pb (stable)

Figure 3.8-1. Uranium-238 Natural Radioactive Decay Series

with materials such as calcium carbonate (7). In the milling process, the sandstone is broken down and after the uranium (and sometimes vanadium) is extracted by chemical leaching, essentially the whole original mass remains as tailings. The tailings consist of the original sand grains plus slimes made up of materials from between the sandstone grains and waste chemical products of the mill process (7).

Sampling of the material flow streams at numerous points in several mills has shown that the tailings contain essentially all of the radioactivity that was originally in the ore except for the uranium; usually less than 10 percent of the original uranium content remains in the tailings (7,8). However, analyses of samples from inactive tailings piles show lesser radioactivity concentrations than expected from uranium concentrations in the ore (9,10,11). The principal decay chain in the tailings radioactivity is that beginning with uranium-238 and ending with lead-206; among the many members are the long-lived radionuclides thorium-230, radium-226, and lead-210. The thorium-230 is the effective beginning of this decay chain in the tailings. The other radionuclide decay chain present, beginning with uranium-235 and ending with lead-207, contributes about 5 percent of the total radioactivity. There are no reports of radionuclides found in the tailings in appreciable concentrations which are not members of either of these two decay chains. For the majority of the uranium ores mined in the United States, the ratios of the concentrations of the radionuclides in the decay chains are approximately the ratios expected under the condition of secular equilibrium (7). If the uranium-238 decay chain was in undisturbed secular equilibrium, for each 0.1 percent by weight of uranium oxide (U_3O_8) that had been in the ore, the tailings should contain about 200 pCi/g of thorium-230, of radium-226, and of each of the succeeding members of the decay chain. Measurements of the radionuclides in the tailings show that commonly the activity of the thorium-230 in the tailings is about the same as the activity of the radium-226 (11,12).

The radioactivity that was pumped to the tailings pond was disproportionately divided between the sands, the slimes, and the dissolved material (7). The dissolved material generally contained less than one percent of the mass and less than one percent of the radioactivity of the tailings (7,8). Although there is considerable variation from mill to mill, the slimes solids are usually about one-third of the total weight of tailings solids and have most of the radioactivity, about three-quarters of the total. It is inferred from a statement of Talvenheimo et al. (7) that the slimes particles may be as fine as minus-400-mesh (less than 25 micrometers in diameter) like particles of silt or clay, and that the sands are generally plus-200-mesh (greater than 74 micrometers in diameter), i.e., in the normal size range for sand particles.

Guiot, Olson, and Schiager (44) have measured radon emanation from the sand fraction of tailings from the Grand Junction pile and determined that about 20% of the total radium inventory in the sand releases radon to the atmosphere. This emanating fraction will be assumed to apply to the slimes also, although Pearson (44) indicates that the smaller particles may release a greater fraction. The overall release from tailings particles is assumed to be about 20% of the total radon produced by the decay of radium-226.

The 20 percent emanation fraction does not completely determine the radon release rate from tailings piles. Radon released at a depth in the pile must migrate to the surface, and may decay during the process. This migration of the radon, a diffusion process, produces a rate of radon emission from the upper surface of the pile which, for a given uniform radon production rate within the pile, is a function of the depth of the pile. This rate approaches an upper limit as the pile depth is increased. Schiager indicates the depth at which the limit is approached by stating that, for dry tailings, "3 to 10 feet in depth is required to produce the maximum radon flux" at the surface of the pile (8). This may be considered an "infinite thickness," i.e., a thickness such that the rate at which radon released from all greater depths (even if they were infinite) reaches the surface is insignificant in comparison, increasing the total release rate negligibly. Schiager also provides a relation between the radon emission rate and the radium content. He estimates on theoretical grounds that at the maximum rate of radon emission from the tailings, 1.6 pCi/m²-s radon-222 are released for each pCi/g radium-226 in the tailings (8).

A variety of factors influence the rate of radon release from a tailings pile. The radon release rate at any one location is known to vary over a factor of 10 due to effects of weather, i.e., wind speed, barometric pressure, atmospheric stability, rainfall, and snow cover (44). Moisture in the tailings is particularly effective in reducing the emission rate; calculations (44) indicate that completely saturating a dry tailings pile with water will reduce its radon emissions by a factor of about 30. Other data (44,44) indicate that addition of moisture occupying 15 to 25 percent of the interstitial space will reduce the emission rate by a factor of 2 to 3. It has been estimated from theory that a 2-foot layer of soil over the tailings will also reduce the radon emission rate by about 95 percent (44).

A list of inactive uranium mill tailings piles is given in table 3.1-1. The piles average 15 acres in area, with a range from 4 to 107 acres. Their average radium-226 concentration is

about 620 pCi/g with reported concentrations (estimated from uranium production records) ranging from 90 pCi/g to 980 pCi/g. Assuming a uniform density of 1.6 g/cm^3 (11), the average depth of all piles, calculated from their reported areas in table 3.1-1, is about 4.8 m, ranging from 1.5 to 17.6 m for individual piles. The piles are frequently roughly rectangular, but in general irregular in shape and, if unstabilized, are made more irregular by wind erosion. Table 3.1-1 indicates that about two-thirds of the piles, both by number and by area, have been stabilized to some degree. Photographs of more than a dozen tailings piles are in references (11) and (18). The Phase I study referred to in the introduction has produced recent photographs of these piles.

The overall radon emission rate from tailings piles may be estimated by applying the theoretical factor of 1.6 pCi/m^2-s radon-222 released per pCi/g radium-226 in the tailings to the areas and concentrations in table 3.1-1, with adjustments for conditions which influence the emission rate. Because the analyses of samples from tailings piles (9,10,11) indicate lower radium-226 concentrations than those of table 3.1-1, a corresponding value of about 4/5 the average will be used, i.e., 500 pCi radium-226 per gram will be used in all calculations that project the potential exposures from an "average" inactive uranium mill tailings pile.

Based on meteorological data for the region (1/;18;19;20), it is assumed that during the year, as a result of precipitation and freezing weather, there are about 80 days during which the release rate is reduced to 1/3 of the value for dry tailings. In effect, this reduces the yearly value by 15 percent. This may be conservative, because some piles are moist years after cessation of mill operations (9).

An adjustment may be considered for areas of tailings piles which have less than an "infinite thickness" of tailings under them. Although each pile is less than the "infinite thickness" at its edges, and although about one-quarter of the piles average less than 3 meters in depth, the overall effect of areas having less than the "infinite thickness" is small, and is estimated from the information given by Schlager (8) to be about 5 percent.

The overall radon-222 emission rate per unit area for the average unstabilized tailings pile is estimated from these considerations to be 500 pCi/g [illegible] x 1.6 pCi/m^2-s [illegible] per pCi/g [illegible] = 0.85 x .95 = 650 pCi/m^2-s radon-222. For the average stabilized pile, this rate is estimated to be reduced by one-quarter to 480 pCi/m^2-s radon-222 (8).

For the average inactive unstabilized pile of 15 acres, the total radon-222 release rate for the pile is about 90 uCi/s (2,900 Ci/yr). For a similar stabilized pile, 68 uCi/s (2,200 Ci/yr). For

the more than 800 acres of piles in table 3.1-1, the total is about 2 mCi/a (5×10^{9} Ci/yr).

3.1.2 Radioactive Particulate Material

The radium-226, thorium-230, and more than a dozen other radionuclides in tailings piles are associated with particles which are picked up by the wind and transported through the environment. This discussion will concentrate on those radionuclides whose presence in the air is clearly due to wind action and on the thorium-230 in particular, because it is among the more hazardous once inhaled.

The ability of the wind to pick up and transport particles depends on the size and density of the particles and on the local wind speed. It is likely that the wind picks up only small numbers of particles bearing thorium until the wind speed is sufficient to allow the wind to move the larger sand grains. Under such conditions, the wind will pick up sand particles and with them the finer particles that were once the tailings slimes. The smaller particles have an unknown size distribution but indications are that an appreciable fraction are smaller than 15 micrometers in diameter (7). The larger grains are deposited quickly, after a short travel distance. At one site, it has been noted that wind-carried tailings on the ground are readily visible beyond the original pile for some 500 feet in the predominant wind direction (11).

Meteorological data (7,10,11) indicate that, allowing for rain and snow cover, roughly 10 percent of the time the wind may have the opportunity and sufficient speed to blow the tailing material around, and about 0.1 percent of the time heavy dust blowing occurs. It is likely that moisture is of lesser consequence in this case, as the surface layers dry quickly. The data are insufficient to permit determination of a quantitative dependence upon the wind speed. Stabilized piles are sometimes considered as if they release no tailings particles to the air. However, it appears that, due to the spread of contamination during the period preceding stabilization, some particulate radionuclides are available for resuspension from the surroundings in every case. This is supported by measurements showing higher than background concentrations (0.004 and 0.008 pCi/m^3 thorium-230) in the air upwind of piles (11).

Reported data (8,10,11,12) indicate that average exposure rates on tailings piles may be about 10 rem/year to the pulmonary region of the lung from airborne radium, thorium, and uranium, and in the general range of 0.01 to 4 rem/year within 1,000 m of

the pile, with most data in the range of 0.1 to 1 rem/year. Measurements made under dusty conditions show exposure rates sometimes exceeding the equivalent of 50 rem/year at locations on wind-deposited tailings near the pile (44).

Thorium-230 and other uranium-related radionuclides are normally present in the air due to wind erosion of natural soil which contains concentrations on the order of 1 to 3 pCi/g of these radionuclides (43,44), with additions to the air from the burning of coal and other human activities. Their normal background concentrations in air in the general environment are estimated from reported uranium concentrations (43) to be in the range of 0.00001 to 0.0003 pCi/m^3.

A peculiarity of reported particulate concentrations in air in the vicinity of inactive mill tailings piles is that many show uranium concentrations comparable to the radium and thorium concentrations, although milling operations commonly remove more than 90 percent of the uranium. Some of the airborne uranium may originate with ore fragments contaminating the mill site. However, it is difficult to believe this contamination is the principal source of uranium in particulates because of the implication that it is also the source of the thorium and radium, thus regenerating the tailings pile.

3.1.1 External Gamma Ray Exposures

Tailings piles containing radium-226 are large enough so that for purposes of calculating the gamma ray exposures at the surface of the pile near its center, they may be treated as radiation-emitting slabs of infinite area. Every disintegration of an atom of radium-226 eventually results in the production, through decay of its daughter products, of an average of 0.18 photons. These photons have a mean energy of 0.834 MeV. More than 95 percent of this gamma energy is from radon daughters (44). The total gamma ray flux at the surface of the pile is made up of unscattered primary gamma rays and secondary gamma rays that have been scattered by material inside the pile but still reach the surface. The primary gamma ray flux is a function of the gamma ray emission rate and energies, the linear attenuation coefficient of the tailings, and the thickness of the tailings. The secondary or scattered gamma ray flux may be described by a buildup factor which is a function of the linear attenuation coefficient, the energy of the primary gamma rays, and the thickness of the slab.

Schiager (8) has performed some theoretical calculations for uranium mill tailings piles and has reduced them to the following:

$$\dot{\alpha}\ (\mu R/hr) = 2.5\ q_{Ra}\ (pCi/g)$$

This simple formula allows the estimation of the exposure rate (x) above a tailings pile if the concentration of the radium in the tailings is known. Schlager assumed that the density of the tailings pile was 1.6 g/cm^3 and that the linear attenuation coefficient was 0.11 cm^{-1}. The buildup factor increases only slowly after 1 to 2 feet of tailings. Thus, the formula, which includes buildup, does not have to be corrected unless the depth of the tailings is less than about 1 foot, in which case the exposure at the surface of the pile will be smaller than predicted by this equation.

Moisture in the pile increases the gamma radiation field because of greater retention of radon which decays to gamma-emitting daughters. Conversely, moisture reduces the gamma radiation by increasing the mass of material with which the gamma rays interact before escaping from the pile.

For the average pile containing 500 pCi/g of radium, the gamma exposure rate at the surface is estimated to be approximately 1,300 uR/hr or approximately 10 R per year. In theory, each foot of packed earth (1.6 g/cm^3) covering the pile (6) will reduce this exposure rate by a factor of approximately 10; it would require only about 4 feet of earth to reduce the exposure rate at the surface from the pile to 1 mR per year. Diffusion and decay of radon-222 in the soil will, however, produce gamma emissions from the upper layers, thus counteracting in part the decrease in the gamma field due to attenuation. For a typical uncovered tailings pile, it is estimated that the exposure rate will decrease to less than 1 mR/yr at 1.0 kilometer.

Experimental measurements of the gamma radiation over the Vitro uranium mill tailings pile by Salt Lake City have been made using TLD dosimeters (5). This pile has been reported (table 1.1-1) to contain about 900 picocuries radium-226 per gram. Schlager's equation using this concentration would predict an exposure rate on the surface of this pile of 1.2 mR/hr. TLD readings, 1 foot above the surface of the pile, ranged from 0.2 to 1 mR/hr at the edge of this pile and from approximately 0.4 to 2.4 mR/hr at the center of the top surface of this pile. These predicted and measured dose rates are in reasonable agreement.

4.4 Airborne Dispersion of Radionuclides

The radionuclides released from the tailings pile surface are mixed into the passing airstream by local turbulences and carried off by the wind, which continually decreases the concentration by mixing and dilution. This process of airborne dispersion eventually delivers a dilute concentration of radionuclides to the downwind locations of people who may inhale them.

Tailings piles are in general large in area and not very high compared to the distances across them. For computational convenience, an example tailings pile has been chosen as a flat circular area emitting radon-222 uniformly over its area. The circumstances considered were the single plume case in which the wind blows continuously from one direction, and the annual average case in which the set of different wind directions and velocities occurring over a year are treated.

There are several methods for treating single plume dispersion from area sources. It may be modeled by a virtual point source or by a line source (28). It may be treated by integrating over the source, analytically or numerically (27). For exposures near or on the source, it may be treated by considering a volume of air moving over the area source (8). The evaluations made in this study were accomplished using a numerical integration over the area source for the single plume cases, and using a line source representation for the calculation of annual average exposures. The area source considered is a circular area with a 400 m (about 1/4 mile) diameter; it has an area of about 31 acres, a little smaller than the 35 acre average area of inactive piles. The single plume results were obtained from an adaptation of the RRAC code (28), and the annual average results from an adaptation of the AIRDOS code (29).

Meteorological data from the Ft. St. Vrain reactor site were adopted for the calculation of annual average exposures because the detailed meteorological data required for these calculations were not readily available for any of the specific tailings pile sites (17). Although the Ft. St. Vrain reactor is not in the neighborhood of a tailings pile, it has meteorological conditions with many points of similarity to those at many tailings pile locations, including a highly anisotropic wind rose (30), in which the wind frequency ranges from 3.9 to 17 percent per 22.5 degree compass sector.

3.3 Radon-222 Dosimetry

When a person breathes the air downwind of a tailings pile, he inhales the dilute concentration of radionuclides in the air. The effect of the radionuclides depends on the nature of the radiation they emit, on the rate at which they emit radiation, on the parts of the body they are retained in and the period of time retained there, and on the manner in which the radiation interacts with the body tissues on a microscopic scale. The significance of radon-222 is believed to be primarily due to its radioactive decay products; it is the inhalation of these decay products which is considered to be a cause of cancer in the tracheobronchial region of the lung.

When the radon-bearing airstream is flowing around a building, the radon enters the building through the ventilation system and through the cracks and openings in it. Some of the radon daughters entrained in the air enter also, and additional amounts of radon daughters are formed in the air inside the building during the period the air remains there before the ventilation replaces it with more air from outside. Thus, the air inside a building downwind from a tailings pile will probably have greater concentrations of radon daughters than the air outside. The time period available for formation of greater indoor concentrations of radon daughters depends upon the ventilation rate; for normal ventilation (11) an amount of air equal to that contained within the structure leaves it and is replaced at least every hour. Ventilation rates of 2 to 6 changes per hour are common. The levels of radon daughter products, greater than 0.01 WL, measured in buildings adjacent to the Salt Lake City pile may be partly attributed to the retention of radon in the structures (5).

The assumption is made that an average individual chronically exposed to a concentration in air of 1 pCi/m^3 of radon-222 receives a radiation dose of 4 mrem per year to the lung from radon daughters (1). This dose conversion factor is in agreement with recommendations in a recent UNSCEAR report (12) and assumes the person is inside a building with adequate ventilation, a quality factor (Q) for alpha particles of 10 and a penetration depth to cells at risk (bronchial epithelium of the lung) of 50 μm. It does not represent the worst conceivable case; but, because of uncertainties, it is considered an acceptable conversion factor for estimating the average dose to large segments of the general population.

There are many uncertainties when the dose to the lung is calculated from exposure to a known concentration of radon-222 (11). The estimated dose is a function of:

a. The degree of equilibrium between radon and its radioactive daughters.

b. The fraction of daughter ions which remain free, or unattached to aerosols at the moment of inhalation.

c. Assumptions with regard to the critical mode of exposure to certain tissues within the lung. Cancers in uranium miners considered to have been caused by excessive exposure to radon daughters, predominantly appear in the area of the large bronchi and are believed to occur as a result of deposition of alpha particle energy in the basal layer cells of the upper bronchial epithelium.

Table 3.3-1 (33) gives calculated alpha dose rates to the basal cell nuclei of segmental bronchi resulting from the inhalation of short-lived radon-222 daughter products in air containing 1 pCi/m³ radon-222. The dose rate resulting from a given concentration of radon-222 is seen to have a wide range of values depending on the conditions of the exposure and the assumptions regarding the critical mode of exposure to tissues of the respiratory system.

Working level months (WLM) is a term commonly used to express a miner's calculated exposure to radon daughter products found in mine air. This unit is derived from the working level (WL), a unit which is defined as any combination of short-lived radon daughters in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy (34). A working level month (WLM) is the exposure to 1 WL concentration of radon daughters for 170 hours or an equivalent product of radon-daughter concentrations and time.

If the concentrations of radon daughters are known (or assumed) relative to the concentration of radon, the WL concentration can be expressed in units of pCi/m³ radon-222. For a daughter ratio of 1.0/0.9/0.5/0.15, which is the ratio assumed for dose calculations in this report, 1 pCi/m³ of radon-222 is equivalent (table 3.3-2) to 3×10^{-6} WL. This same ratio was used to calculate the radiation dose of 4 mrem/yr resulting from chronic exposure to 1 pCi/m³ radon-222. These relationships are summarized in table 3.3-2.

3.4 Airborne Thorium-230 and Radium-226 Dosimetry

Table 3.4-1 gives the dose conversion factors for thorium-230 and radium-226 used to estimate the average dose to large segments of the general population (1).

Particulate material from a tailings pile that is lifted into the air by the wind will contain thorium-230, radium-226, and radon-222 and its daughter products. If these particles are inhaled, the resultant radiation doses will depend primarily on:

a. The activity levels of the radionuclides.

b. The particle size distribution of the aerosol particles.

c. The solubility of the particles in fluids of the lung.

d. The energies of the alpha particles emitted in the lung.

Table 3.1-1. Calculated Alpha Dose Rates (millirem/yr) from Inhalation of Short-Lived ^{222}Rn Daughter Products to the Basal Cell Nuclei of Segmental Bronchi (a)

	Penetration Depth in Cells in μm (cm)				
	10	30	50	70	90
Living Accommodation; adequate ventilation(a)	60	35	8.9	3.6	0.19
Living Accommodation; inadequate ventilation(b)	99	51	13	4.7	0.18
Industrial Premises(c)	115	61	25	10	0.41
Air Conditioned Sites(d)	72	36	13	5.0	0.15

(a) ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Bi concentrations: 1.0, 0.90, 0.91, 0.95, pCi/m^3 respectively;
(b) ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Bi concentrations: 1.0, 0.93, 0.78, 0.97, pCi/m^3 respectively;
(c) ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Bi concentrations: 1.0, 0.97, 0.84, 0.78, pCi/m^3 respectively;
(d) ^{222}Rn, ^{218}Po, ^{214}Pb, and ^{214}Bi concentrations: 1.0, 0.88, 0.40, 0.95, pCi/m^3 respectively.

Table 3.1-2. Conversion Factors and Equivalents for Radon-222 and Daughters

Concentration of Radon-222	Working Level	Dose Equivalent
Continuous[a] exposure to [illegible] pCi/m³	Continuous exposure to [illegible] WL	4 mrem/year to the lung[b]
Continuous exposure to 3×10^3 pCi/m³	Continuous exposure to 1 WL[c]	8×10^3 mrem/year to the lung
Continuous exposure to 0.33 pCi/m³	Continuous exposure to 1.3×10^{-6} WL	1 mrem/year to the lung

(a) Assumed radon-222 and daughter ratios 1.0/0.9/0.5/0.15 (for living accommodation with normal ventilation).

(b) Dose delivered to basal cell nuclei of segmental bronchi; 0, 10; penetration depth to cells at risk, 50 μm.

(c) A combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy.

Table 3.4-1. Dose Conversion Factors for Airborne Thorium-230 and Radium-226 (A)

Radionuclide	Solubility (class)	Critical Organ	Dose Conversion Factor mrem/yr per pCi/m³
Thorium-230	Soluble (D)	Bone	30,000
	Insoluble (Y)	Lung[a][b]	11,000
Radium-226	Soluble (D)	Bone	900
	Insoluble (Y)	Lung[a][b][c]	11,000

(a) Pulmonary region of the lung.

(b) Assumes particle has an AMAD of between 0.3 and 1.0 μ, the pulmonary region of the lung weighs 250 gms, and the mean retention time of an insoluble class Y particle is 1,000 days in the pulmonary region of the lung.

(c) Assumes only radium-226 contributes to the dose and not radon-222 nor its daughters.

The probability of inhaled particles being retained in the lung is determined by the particle size distribution of the aerosol (11). Some of the particles are exhaled, and a fraction of the others that is initially retained in the lung is subsequently removed to the gastrointestinal tract. Of the remaining retained particles, those that are insoluble will remain a long time and deliver their radiation primarily to their region of the lung; those that are soluble are dissolved and their radionuclides will be translocated by the blood to other organs where they may be retained selectively. Soluble thorium and radium are bone seekers; thus, the critical organ doses will be delivered to the bone.

Dose conversion factors given in table 3.4-1 are suitable for aerosol particles with a particle size distribution characterized by an activity mean aerodynamic diameter (AMAD) of 0.5 to 1.0 micrometer. As an illustration of the effect of particle size, table 3.4-2 gives the deposition of particles in the pulmonary region of the lung as a fraction of the AMAD and indicates how the dose conversion factor could change as a function of particle size distribution. For insoluble particles, the dose conversion factors are also directly related to the mass of the pulmonary region of the lung (430 g) and the mean residence time of particles in the lung (t_b = 1,000 days). For insoluble particles with a t_b of 350 days and an AMAD of 5 micrometers, the dose conversion factors could be as much as a factor of 10 smaller. The dose conversion factors in table 3.4-1 represent upper limit or conservative values, with the exception of the assumption that only the radium contributes to the dose, and not its decay product radon-222 nor radon daughters.

3.5 Gamma Ray Exposure

The gamma ray exposure from the surface of a uranium mill tailings pile is assumed to be whole body radiation potentially delivering an absorbed dose with a quality factor of 1.0. The exposure rate in mR/hr is therefore assumed equal to a dose equivalent rate in units of mrem/hr to the whole body.

4.0 Results

4.1 Air Concentrations

Figure 4.1-1 shows the radon-222 concentrations in air as a function of distance for a single plume from an area source compared with those from a point source. The downwind distance is measured from the center of the area source to the receptor.

Table 1.4-2. Percent Deposition of Particles in the Pulmonary Region of the Lung as a Function of Activity Mean Aerodynamic Diameter (μm)

Particle AMAD Micrometers	Deposition of Particles in the Pulmonary Region of the Lung
10	9
5	11
2	20
1	25
0.5	31
0.2	40
0.1	36

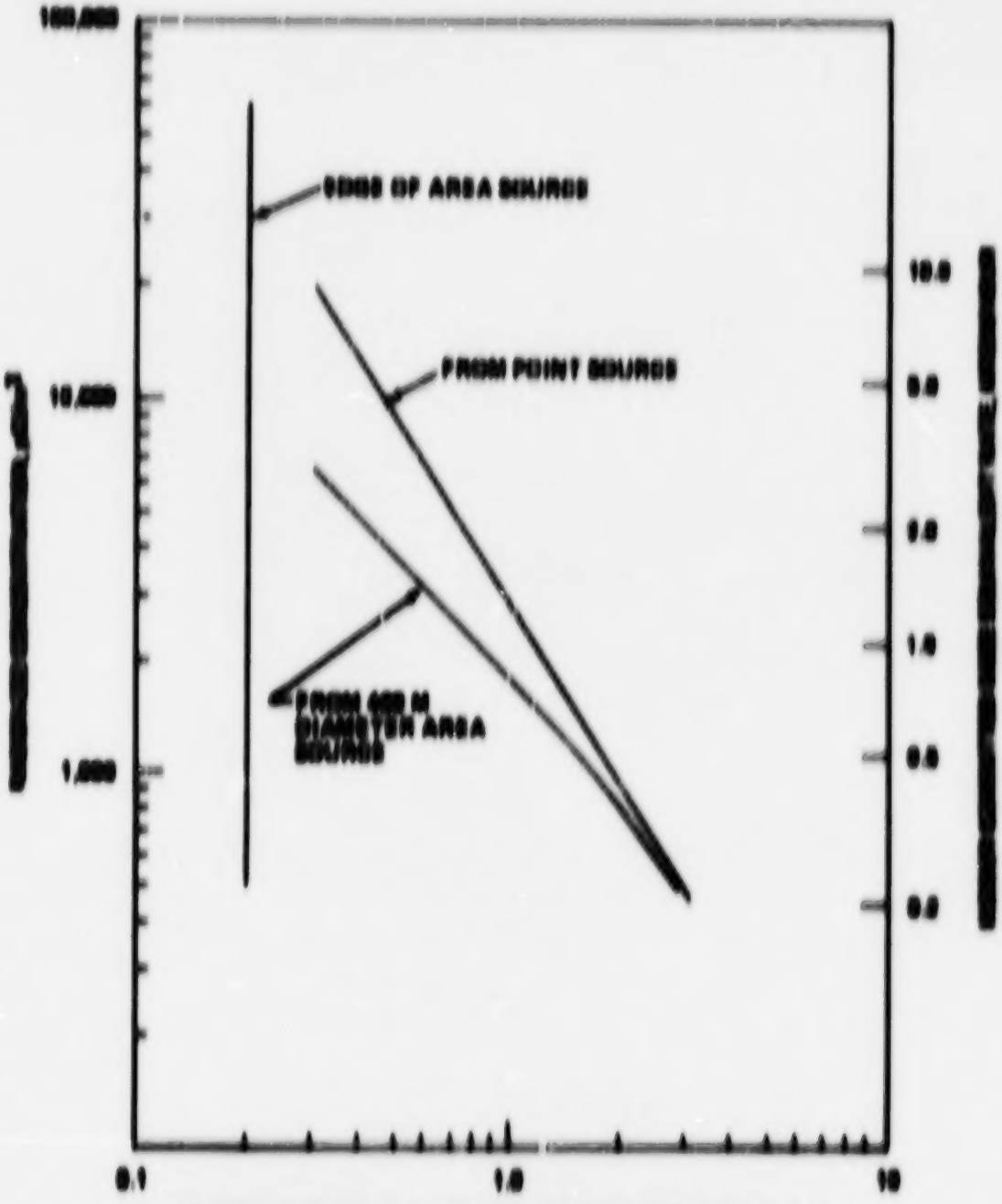
EDGE OF AREA SOURCE
FROM POINT SOURCE
0.1
1.0
10
DOWNWIND DISTANCE FROM CENTER OF AREA SOURCE, km

FIGURE 6.1-1

Figure 4.1-2 shows a similar comparison of the radon-222 concentrations in air as a function of distance in the cross-wind direction at a downwind distance of 500 m.

Figure 4.1-3 shows the calculated annual average radon-222 concentrations as a function of distance and averaged over all directions, compared to the measured data from which table 3.1-1 was compiled (3). The majority of the measured concentrations did not differ appreciably from the concentration assumed to be the local background. Only measured results which did differ appreciably from background are shown; their statistical error ranges well over 100 percent.

4.2 Radiation Doses

If the dose conversion factor of 4 mrem/yr per pCi/m³ radon-222 is applied to the radon-222 concentrations in Figure 4.1-1, the dose to the bronchial epithelium of the lungs of persons in buildings at the respective distance from the center of the tailings pile is obtained. The estimated average radiation dose due to radon emission is about 8 rem in the lung per year at 50 m from the edge of the pile, about 0.3 rem per year at 1 km and about 0.1 rem per year at 1.5 km.

For individuals outdoors near tailings piles, the exposure to the airborne decay products of radon-222 released from the pile is probably insignificant, because of dilution by the wind before much radioactive decay occurs. However, most people spend the majority of their time indoors.

Another mode of exposure is that from particulate radioactive material airborne due to wind action. The average exposure rate from airborne uranium, thorium, and radium to the lungs of individuals within 1.0 km of a tailings pile is estimated to be generally one-third or less of that from decay products of radon released from the pile. The principal exposure from the particulate uranium, thorium, and radium is believed to be to the non-ciliated, pulmonary region of the lung, in contrast to the principal exposure by daughters of airborne radon being in the bronchial epithelium. Another contrast between these modes of exposure to the lung is that the exposure from particles is likely to be less indoors than out, because of removal of particles by filtration and sedimentation from the airstream entering a building.

The average exposure rates from gamma radiation to the whole body are similar to the exposure rates to the lung from airborne uranium, thorium, or radium at locations close to a tailings pile, but decrease more rapidly with distance, to less than 1 mR/year at 1.0 km.

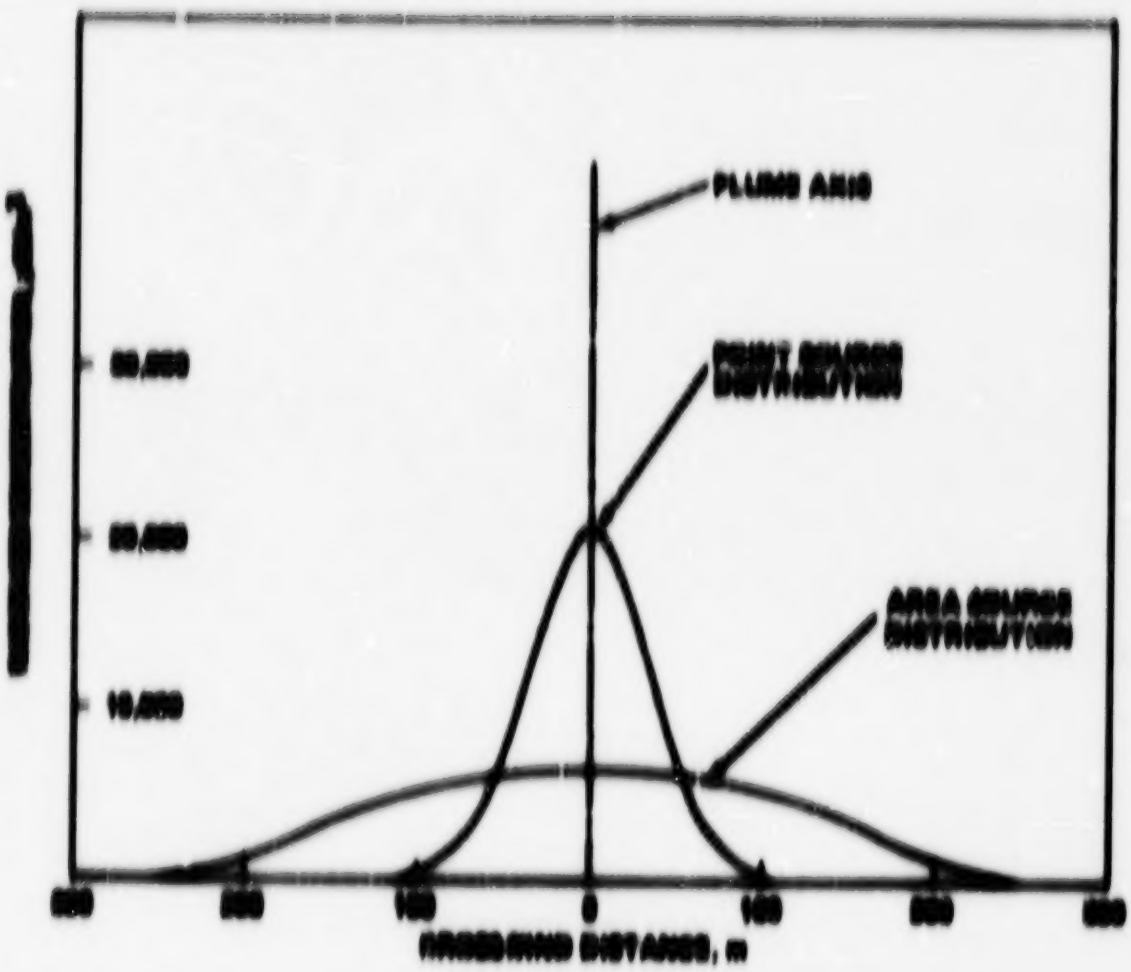

FIGURE 6.1-2

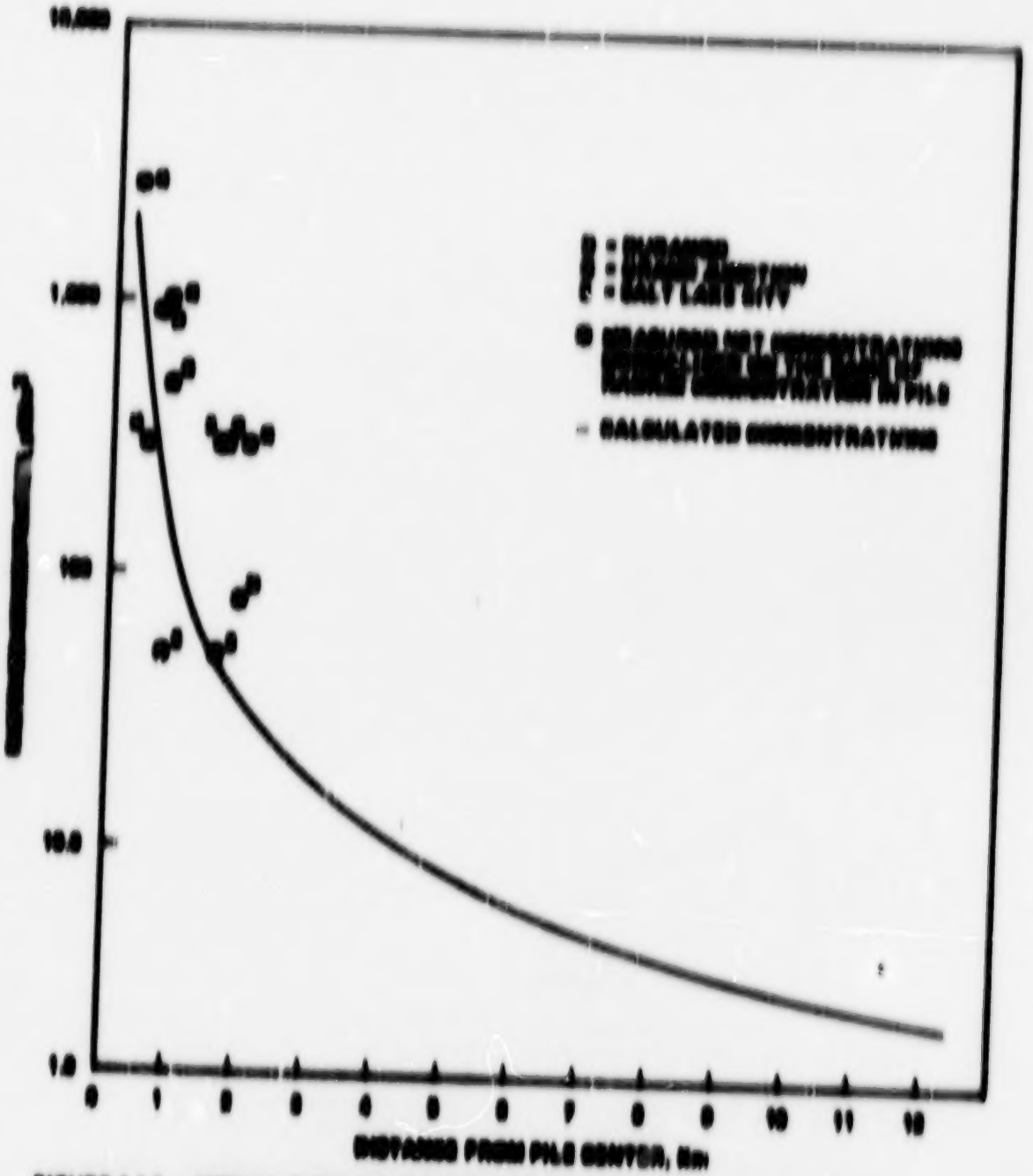

FIGURE 6.1-3

The presence in the neighborhood of contamination such as scattered ore fragments and windblown tailings may cause exposures to remain higher with distance from the pile than these estimates indicate.

5.0 Discussion

Radiological dose assessment calculations were performed for the average, uncovered, dry tailings pile (1.) a 10^5 m^2 (25 acres) containing 500 pCi/g each of thorium-230 and radium-226. For piles of different radionuclide concentrations, the results given in Figure 4.1-1 can be scaled linearly to estimate approximately the corresponding radiation dose rates. For example, the Vitro pile is approximately 3 times larger and contains almost twice the radioactivity as the average pile. Therefore, allowing for its size, radiation doses from radon and thorium are expected to be 3 times greater in adjacent areas and, at a distance, 5 or 6 times greater than those predicted for the average pile. In addition, the dose rate in the prevailing wind direction may be twice that of the average dose rate. The "worst case" is assumed from the Vitro pile where dose rates in buildings adjacent to the pile are estimated to be about 3 times that predicted for the average dose rate in the vicinity of the average inactive tailings pile.

The credibility, accuracy, and precision of estimates of dose equivalent from emissions from tailings piles can be greatly improved with site-specific information on:

a. The emission rate of radon from inactive piles, experimentally measured.

b. Meteorological data, assembled for the inactive piles for comparison with assumptions used in this report.

c. Population data around each pile.

d. Measurements of airborne radionuclide concentrations, correlated with meteorological conditions.

e. Activity vs. particle size distributions of airborne particles containing thorium-230 and radium-226.

5.1 Results for the Average Inactive Tailings Pile

For persons in dwellings in the neighborhood of a 25 acre inactive tailings pile assumed to contain 500 pCi/gm radium-226, the estimated average radiation dose rates are given in

section 4.5. These dose rates, high in comparison to those around nuclear facilities, indicate a need to evaluate measures to reduce exposures near inactive tailings piles.

The comparison of the area source with a point source indicates that the size of the source causes average concentrations of radon in the neighborhood of a pile to be more evenly distributed around the compass than average concentrations from a point source. Thus, a location upwind of the pile in the most frequent wind direction will not be as favored as might be expected from the wind frequency data.

The results indicate that the suspension of fine particles by the wind is not as large a problem as that of the radon emissions. Stabilization of piles by addition of a foot or more of soil cover is believed to effectively stop further spread of wind suspended contamination as long as the cover is not displaced; previously distributed contamination not cleaned up at the time of stabilization can continue to contribute small dose rates.

Similarly, the potential gamma radiation dose rates, ranging up to about 10 rem/yr on a tailings pile, may be largely avoided by stabilization of the pile with one or more feet of soil cover and cleanup of distributed contamination. The permanence of the benefits of such stabilization may be questioned. Measurements at the Monticello pile indicate that the cover soil has reduced the gamma exposure rate by a factor of about 5 [23].

Data in the report "Evaluation of Radon-222 Concentrations Near Urantum Tailings Piles" [2] may be compared to the estimated average values of the example calculation, shown in Figure 5.1-1. The data representing measurements on the piles (see Table 5.1-1) may be compared to the estimated value in Figure 4.1-3 of roughly 3,000 pCi/l at 50 m from a pile; all average concentrations on piles are higher, some by a factor of 5. Annual average concentrations measured in Durango, Grand Junction, and Salt Lake City [2] are plotted in Figure 5.1-1 for comparison, after subtracting background. Predicted values are not in major disagreement with the measured values, considering their wide scatter.

It appears from the results of this assessment that the principal long term radiological health problem associated with tailings piles is caused by radon releases. The critical pathway is radon emission from the pile surface followed by diffusion, buildup in dwellings long enough for radon daughters to grow in, and finally radiation exposure to the lung due to the inhalation of the radioactive daughters of radon. Radon is not appreciably contained by covering the pile with a few feet of earth cover.

Therefore, the evaluation of remedial actions for individual tailings piles to prevent excessive exposure to members of the general population must include a consideration of the radiation dose delivered through the radon exposure pathway.

Particulate material of respirable size carried off a pile by wind delivers a radiation dose to the lung which is less than the radon dose. Radiation exposure through this pathway appears to be relatively easily controlled by stabilizing the pile with a few feet of earth cover. Direct gamma radiation from the pile is also reduced although not eliminated by a few feet of packed earth.

Radioactive material may be carried from the pile by winds or by human actions, creating offsite exposures from radon and from gamma radiation. Wind action brings tailings and consequent radiation exposures to locations whose distance once provided appreciable protection from the radioactivity in the pile. Radium can be leached from the pile if the pile is exposed to water. These are special cases of contamination, not considered in this report, that must be considered for each individual tailings pile site.

When radon-222 is released from a tailings pile there is, in addition to the exposure of persons living near the pile, a potential for national and world wide exposure. Radon being a noble gas does not deposit quickly on the ground like particulate matter; thus, the 3.8 day half life allows sufficient time for wind to carry most of the radon very long distances before radioactive decay occurs. At long distances from the pile, the radon-222 exposure pathway is identical to the local exposure pathway. But in addition to the radiation dose to the bronchial epithelium caused by short half-life daughters, radon-222 eventually decays to long half-life radionuclides of lead, bismuth, and polonium. These deposit on the ground and have a potential for radiation exposure through food pathways. These potential national and world wide radiological impacts are not evaluated in this report. They are very small when compared to the natural radiation background as caused by these same radionuclides.

9.0 Uncertainties

The radiological assessment of uranium mill tailings piles performed in this report makes use of some parameters for which the values are not well known.

9.2.1 Source Term

One of the primary factors affecting the emission of radon-222 is the quantity of its precursor, radium-226, that is in the tailings. Under the assumption that the radium-226 content of the ore is in secular equilibrium with the uranium-238 content, the quantity of radium-226 that went to the tailings at each mill site has been estimated from the mill's production records; the values in table 9.1-1 were derived in this manner. Analyses of samples from tailings piles (9,10,11) show smaller concentrations, down to half the expected value. Whether these discrepancies are due to errors in the predicted concentration or as a result of sampling which is not representative is not clear; individual samples from the Mexican Hat pile differed by a factor of 3 or more (9). The ratio of sand to slimes particles in the sample may influence the analysis, as the slimes solids contain higher radium-226 concentrations. It is probable that in some instances the assumption of secular equilibrium is incorrect; for example, ground water may have leached some elements from the ore. A review of analyses of more than 90 soil samples (12) having radioactivity concentrations characteristic of uranium ore (i.e., concentrations of radionuclides that, in equilibrium, would be associated with uranium concentrations greater than 0.05%), showed that about one-third had concentrations of radium-226 and thorium-230 within 10% of equilibrium and one-third had concentrations differing from equilibrium by more than 50%, the remaining third falling in between. At Mexican Hat, the sample analyses show thorium-230 concentrations five times the radium-226 concentrations (9). In general, either case is possible; that the ore had uranium-238 radioactivity greater than its radium-226 radioactivity, or smaller.

The radon emitted from the surface of the pile may be assumed to have originated at a distance below the surface which is less than the "infinite thickness;" however, the radium may not be uniformly distributed in the pile. At various times, ores having different radium concentrations may have been processed by a mill, with their associated tailings ending in different parts of the pile. Another factor is the greater radioactivity of the slimes solids (7) because any process that tended to separate slimes solids from sands in the tailings would make the pile non-uniform in its distribution of radium-226, and thus non-uniform in its radon-222 emission rate over the surface. At least one mill had separate tailings ponds for the sands and for the slimes (8).

Another source of uncertainty in the radon emission estimate is the 0.2 emanation fraction. The determination of a 0.33 frac-

tion by Schiager et al. (44), although carefully performed, is properly applicable only to tailings sands from the Grand Junction pile. The emanation fraction may be different for the slimes solids, and may differ from pile to pile. It is unlikely that it is much less than 0.2 and also that it is greater than 0.6.

Although the tailings piles have been discussed in terms of an average pile, they are not uniform in character. Though frequently roughly rectangular, the piles are generally irregular in size and shape. Several of the piles listed in Table 7.1-1 are actually two or more piles in the same vicinity, with the possibility that each has individual characteristics as a radioactivity source.

The piles may vary considerably in the soil characteristics of the material comprising the pile. Some piles, from operations called upgrading operations or concentrators, may be relatively pure sand with little of the fines from the slimes and little radioactivity. This is because the slimes have been shipped to another mill for further processing (7). Piles of this type might be expected to be easily windblown, having no fines to help hold the material together. Other piles may have a large fraction of the fine particles from slimes in their make-up, due to the nature of the ore they came from and possibly to slimes from upgrading operations having been added to them. Reference to piles being muddy (5) and clay-like (9) is reasonable confirmation of characteristics unlike sand. Such piles will retain moisture longer and have reduced radon emission rates as a result. They may also be somewhat less subject to being wind drifted.

These differences in the soil characteristics of a tailings pile affect its relaxation length for radon (a measure of the depth from which radon can migrate to the surface) when wet or dry and the rate at which the pile will dry out when moistened by precipitation. Some piles appear to dry slowly (9); their radon emission rates may be higher in the future when they have dried out. The dry depth available for radon emission may also be restricted by the underlying soil characteristics and topography, which may prevent rapid drainage of moisture from the pile. Moisture, especially together with a high slimes content, will reduce the radon emission rate, but it is unlikely that it would be reduced by more than two-thirds. Moisture may also serve to leach radium and other radionuclides into the underlying soil and possibly into the cover soil if it is applied for stabilization. Stabilizing a pile by the addition of soil and by growing vegetation may further reduce the radon emission rate by the enhancement of moisture retention.

Although we have used a settings density of 1.6 g/cm^3, it is known that the dry density of tailings varies from one pile to another (14). One effect of uncertainty in the density is to introduce uncertainty in our calculation of the average depth of tailings in a pile from its area and tonnage. In regard to other pile characteristics, it should be noted that the slimes solids have been reported as being more dense than the sands (8). The uncertainty in density may also affect the relation (4) between the radium concentration in pCi/g and the rate of radon emission in pCi/m^2-s from the surface of a pile of "infinite thickness." There seems to be some discrepancy among the temperature relating density, emanating fraction, and infinite thickness; if the density (1.6 g/cm^3) and emanation fraction (0.2) are reasonably accurate, the infinite thickness (6 to 10 feet) appears to be underestimated. It is unlikely that the density would be less than 1.4 or greater than 1.8 g/cm^3.

The thorium-230 content of the tailings piles is subject to greater uncertainties than the radium content, because it has not been as widely measured. It has the same types of uncertainties in quantities, concentrations, and distribution as the radium. Since its chemical behavior is different from that of radium, its distribution may be different from the radium, both by natural causes in the ore and by the physical and chemical processes in the mill and tailings.

The soil characteristics of the tailings may also have a large influence on the amount of material that becomes airborne in that a relatively clean sand of coarse grains may not release many particles to the wind whereas tailings susceptible for their dusty appearance may release large quantities (23). Tailings which are subject to wind action may be so blown around that the source is enlarged, and the reported exposures may reflect wind-blown tailings much nearer than the tailings pile. This may account in part for the slow decrease in exposure rate with down-wind distance (23).

Some of the radioactive radon-222 decay products in the air may have been lifted into the air in particulate form (in the same manner as the uranium, thorium, and radium) rather than being formed directly in the air by radon-222 decay. The available data does little to distinguish airborne radon daughters by their history, especially if they are associated with particles. The degree and nature of their association with particles plays an important role in their potential for exposure of different regions of the lung or of other organs. But estimates of doses from radon daughters include only those daughters formed in the air.

Some of the factors that affect the radon emission estimates also affect the estimates of the gamma radiation field around the piles; differences in density, in composition, and in moisture content can affect the linear attenuation coefficient and the buildup factor; the linear attenuation coefficient will vary almost directly with the bulk density of the tailings and thus varies as the moisture content affects the density. Comparison of estimated radium concentrations with measured exposure rates indicates that the theoretical factor employed in the gamma radiation estimates may estimate exposure rates which are high in some cases, perhaps up to a factor of 3. Since most of the external gamma dose is due to radon and its decay products in the pile, the rate at which radon escapes influences the gamma dose rate. Coating the tailings surface with a thin sealing preventing radon escape would be expected to result in an increase in the local gamma field, but not more than 50 percent (44). The external gamma dose rate from the airborne material is 25mil, less than one mrem per year.

8.8.8 Meteorology

The meteorological data employed, from the Fort St. Vrain reactor site in Colorado (47), is different from that at specific tailings piles. The uncertainties due to differences at each tailings location include the uncertainties due to the effects of terrain on the meteorology at low elevations. These effects are quite local so that a good estimate of the annual average dispersion to locations within a half mile of a pile would require data obtained from that neighborhood.

The dispersion of radon from the piles was estimated with adaptations of the common model for Gaussian diffusion from a continuous point source emitting at a uniform rate. The only changes made were to consider an area source rather than a point source. It has been observed that the radon emission rate is affected by meteorological conditions and, thus, is not uniform. One effect is reported to be an emission rate proportional to wind speed (48). Such an effect could deplete the radon in the upper layers of a pile or that following a high wind, the emission rate would be depressed, under circumstances in which the common Gaussian diffusion model would, due to its inverse dependence on windspeed, predict an increased concentration exposure rate. It is possible that there are other meteorological factors, such as variations in barometric pressure and stability of the lower atmosphere, which may cause average exposures to differ from those predicted by the model for a uniform continuous source. Pearson (48) suggests that atmospheric instability may produce a depletion analogous to that suggested for high wind speeds. Either or

both of these depleting effects would lower the annual average exposure to radon from the piles.

It should be noted that not all the airborne radioactivity in the vicinity of an inactive tailings pile originates in the pile. The poor correlation between the direction of the wind across the tailings pile and the measured concentrations (9) lends support to this. Some airborne activity is due to natural background which may be anomalously high because of higher than average radionuclide concentrations in the soils and rocks in the vicinity; and some may be due to contamination of the surroundings by ore fragments and windblown tailings from the mill site (8,9, 10,11). Urban areas may have higher concentrations of some particulate radionuclides in the air due to increased dust levels resulting from vehicular traffic and construction activities (12). Thus, the radioactivity levels reported in the vicinity of several piles (2,3) may arise from several sources. These different sources complicate field measurements and the interpretation of the data obtained. The assumption that the tailings pile is the only source may lead to overestimating its effects.

Several conditions can lead to high dust concentrations and related higher thorium and radium concentrations. The lack of protective vegetation on the tailings piles permits higher wind velocities at the surface so that dust-blowing conditions may result more frequently than on vegetated areas. Measurements made in dust-blowing conditions may show exposure rates ten or a hundred times the average (11).

Dust devils provide another mechanism for providing high dust concentrations and thus higher potential exposure rates (13,14). Dust devils occur commonly on bare dry ground which has been heated by the sun, warming the adjacent air so that it is appreciably lighter than the overlying air (15). Most dust devils last only a few minutes but in some locations they may occur frequently (16). It has been reported that one which lasted several hours removed about a cubic yard of sand per hour (16). Measurements made with dust devils on a tailings pile show exposure rates as much as ten times the average (11). They are unlikely to be present more than a few percent of the time, however.

Since construction activities and vehicular traffic add significantly to dust concentrations (12), allowance should be made in planning actions to stabilize or dispose of tailings piles to avoid unnecessary exposure of workers and persons living in the vicinity.

5.5.5 Dose Conversion Factors

The dose conversion factor for radon-222 is a function of the degree of equilibrium between radon and its daughters, the fraction of daughters which remain unattached to aerosols at the moment of inhalation, and assumptions with regard to the principal mode of exposure to certain tissues within the lung. Depending on the conditions of the exposure and assumptions regarding the way tissues of the lung are exposed, the dose conversion factor ranges widely in value as seen in table 5.5-1. The value of the factor used in this report of 4 mrem/yr per pCi/m³ radon-222 does not represent the worst case, but because of uncertainties it is considered acceptable for estimating the average dose to large segments of the general population.

The dose conversion factors for airborne thorium-230 and radium-226 depend greatly on knowledge of the solubility and size of the radioactive aerosol particles. For thorium-230, the dose conversion factor varies by a factor of 1.5 between insoluble and soluble particles; for radium-226 by a factor of 130. The dose conversion factor for both may vary by a factor of 5, larger or smaller, depending on whether the particle size distribution may be described by an activity mean aerodynamic diameter (AMAD) as small as 0.1 μm or as great as 10 μm. The AMAD value of 0.5 to 1.0 μm assumed in this report is believed to be reasonably typical of airborne particles carried more than short distances by average wind velocities. Measurements reported by Breslin and Glayberman (44) support this assumption; they indicate a respirable fraction (in the pulmonary region) of about one-third.

The solubility of the particles in lung fluids and in passing through the gastrointestinal tract is undetermined. However, experience with uranium mines indicates that most of the ore dust they are exposed to is insoluble (45) and investigations of mill flow streams show that very small percentages of the radium and thorium are dissolved as the material passes through the mill (8). The assumption made is that the airborne particulates in the vicinity of tailings piles are insoluble.

The dose conversion factors used in this assessment for airborne, insoluble particles containing thorium-230 and radium-226 assume that the mass of the lung is 450 g and that the particles have a half-value residence time (T_b) in the lung of 1,000 days. These assumptions, which represent the best judgment of the Environmental Protection Agency, have been selected with a tendency to make the dose conversion factors conservative. For example, if T_b were 350 days, the factors would be 3 times smaller; if the lung mass were assumed to be 1,000 grams, they would be 2 times smaller.

The dose conversion factors used in this assessment for airborne, soluble particles containing thorium-230 and radium-226 and for gamma radiation are derived directly from recommendations of the International Commission on Radiation Protection (ICRP) and as such represent generally acceptable values.

5.0 Health Risk Estimate

There is believed to be a potential health risk to persons living near uranium mill tailings as a result of the pile's radon-222 emissions. The potential health risk associated with this exposure to radon-222 and its daughters is a form of lung (bronchial) cancer considered to be 100 percent fatal. It has a latent period of 10 to 15 years after the onset of radiation exposure that is followed by a plateau period of elevated risk which lasts from 15 years to possibly a lifetime.

The potential health risk from windblown particulate material from the pile is probably not as significant because the radiation dose is smaller than the dose from radon-222, plus the particulate material dose is delivered to the pulmonary region of the lung. The radon-222 dose is delivered to the bronchial epithelium region of the lung, and data from the BEIR (1) report indicates that the bronchial epithelium is much more sensitive to radiation compared to the pulmonary region of the lung.

The potential health risk from the pile's gamma radiation is also of lesser significance because the whole body gamma radiation dose is considerably smaller than the dose to the bronchial epithelium from radon-222 daughter products. While more health effects are produced per unit dose equivalent of whole body radiation than per unit dose equivalent delivered to the bronchial epithelium only, the much smaller relative dose from gamma rays causes the overall potential health risk from gamma radiation to be considerably less than the potential health risk from radon-222 emissions.

Because bronchial cancer is believed to have many possible causes, the bronchial cancer risk from radon daughters is best expressed in terms of the percentage increase in the expected cancer risk, i.e., the relative risk, rather than the absolute number of cancers expected per person-rem of exposure. The relative risk is not considered to be a function of the level of absolute risk and is therefore the same for everyone while the absolute risk of bronchial cancer to an individual depends strongly on his personal history. For example, habitual cigarette smoking may increase the risk of bronchial cancer by a factor of 3 to 10. Because the relative risk coefficient for bronchial cancer from radon exposure is thought to be relatively independent of smoking history, exposure to radon daughters

sufficient to double the risk of bronchial cancer for nonsmokers will also double the risk for smokers.

The health risk associated with exposure to radon-222 and its daughter products cannot be accurately assessed at this time. Although epidemiological studies have indicated increased incidence of bronchial cancer among uranium miners and certain metal, hematite, and felspar miners who have been exposed to high airborne concentrations of radon daughters, the use of health risks derived from these results to provide estimates of risk to members of the general population involves considerable uncertainty. There are many differences between the uranium miner populations and the general population living near tailings piles, and there are critical differences between radiation exposure conditions found in mines compared to houses (38,39).

It is current best judgment that exposure to 110 working level months (WLM) doubles the risk of bronchial cancer in uranium mining populations (42) where "working level months" is a measure of integrated exposure to radon daughter products (36). Because uranium miners usually have chronic bronchitis which reduces the dose owing to the protection provided to the epithelium by the increased thickness of the mucus layer, an equivalent radon daughter exposure level delivers a greater dose to members of the general population than to mining populations. The BEIR report (43) uses a factor of 2 to account for existing chronic bronchitis when estimating the dose to the basal cell layer of the epithelium of the larger bronchi on a probabilistic basis. Therefore, despite uncertainties, 55 working level months exposure will be assumed to double the risk of bronchial cancer for members of the general population.

The general population doubling exposure of 55 WLM lies within the limits of 150 WLM (40) in United States uranium miners and 10 WLM (41) in non-uranium miners which can be obtained in other studies although the uncertainties in risk estimation below 100 WLM is very high (44). This general population risk estimate is still likely to be low by a factor of 2 to 4 because of other significant differences in exposure conditions between members of the general population and the uranium mining population (42) which have not been adequately assessed. The potential risk is assumed to vary in direct proportion to exposure to radon daughter products in units of WLM. Additional discussion is included in Reference (42).

The individual living in the immediate vicinity of the average inactive tailings pile (50 meters) is estimated to receive a potential dose equivalent of 8 rem/yr to the bronchial epithelium. This

dose equivalent is assumed to be equal to an exposure to 0.0 WLM/yr (WL) of radon daughters. It would, therefore, require approximately 100 years of exposure to radon daughters at the rate of 0.1 WLM/yr to double the individual's risk of bronchial cancer. This is the same as a 1 percent increase in potential risk for each year of exposure or a 70 percent increase in potential risk over a lifetime of 70 years. Also, 0.1 WLM/yr is approximately 1/10 of the radiation guidance for the protection of underground uranium miners issued by the Environmental Protection Agency (4). Individuals similarly exposed to 0.1 rem/yr at 1 km and 0.1 rem/yr at 1.6 km incur an increased bronchial cancer risk of about 1 percent and 1 percent respectively for a lifetime of exposure to an average inactive uranium mill tailings pile.

6.0 Conclusions

Atmospheric concentrations of radon-222, thorium-230, and radium-226, and direct gamma radiation levels from inactive uranium tailings piles have been estimated, and the potential radiation doses to individuals in the general population were presented in section 5. These calculations indicate that individuals may be receiving significant doses to the lung out to distances of approximately 1 kilometer from the tailings pile from radon-222 and its daughter products, and that this is the most significant long-term exposure pathway. Since some of these piles are located in or near urban areas, large population groups may be receiving these lung doses, thus increasing the health risks. Stabilization of piles with compacted earth may not be especially effective in reducing the radon emission problem since, in theory, 3 feet of earth cover reduces the emission rate by only about 25 percent and about 30 feet are required to reduce it by more than 90 percent (5).

Windborne particulates containing uranium, thorium-230, and radium-226 which are fine enough to be transported distances of a kilometer or more result in other lung doses which are smaller than those from radon daughters and which are delivered to different lung tissues. Several feet of earth cover are expected to be adequate to stabilize the pile so that wind erosion of radioactive particulates is significantly reduced or eliminated.

The direct gamma radiation exposure rate at about 1 foot from the surface of an average tailings pile containing 100 pCi/g of radium-226 is estimated to be about 1,200 uR/hr (= 10,000 mrem/yr). In theory, each foot of compacted earth cover will reduce this exposure rate by a factor of 10 (5). Therefore, 4

foot of earth cover should eliminate any problems associated with direct gamma radiation doses. The actual reduction in exposure rate provided by earth cover appears to be less and should be confirmed by experiment.

There is considerable need for field studies to refine the various uncertainties discussed in section 5.3. If the potential radiological impact of an inactive uranium mill tailings pile is to be more accurately estimated, the following parameters should be measured:

a. Radium-226 and thorium-230 content of the pile.

b. Radon emission rate from the surface of the pile.

c. Average radon-222 and decay product concentration, the concentration of ambient aerosol particles, particle size distribution, and the fraction of the total potential alpha energy that is uncombined with particles in the environment around the pile out to a distance of at least 1 kilometer.

d. Radon-222 and daughter product concentrations and the fraction of the total potential alpha energy that is uncombined with particles inside a selected number of dwellings around the tailing pile.

e. Direct gamma radiation levels as a function of distance from the tailings pile.

f. Airborne levels of thorium-230 and radium-226 around the pile as a function of distance, both indoors and outdoors, together with the determination of the particle size distribution.

g. Solubility class of the radionuclide bearing particles and their specific activity.

Finally, there is a need to refine dose conversion factors for radon-222 and its decay products, and for thorium-230 and radium-226, under those conditions typical of uranium mill tailings pile sites.

In order to completely assess the environmental impact of [illegible] tailings pile, the total health effects to the population at [illegible] would have to be considered on a national and worldwide [illegible]. This will be the subject of future investigations by the Environmental Protection Agency.

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